Cascaded longitudinal space charge amplifier for short-wavelength radiation generation at FAST

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Motivation and goals

- Longitudinal space charge effects are responsible for unwanted energy modulations and emittance growth in FELs
- On the contrary, such instabilities were shown to be potentially useful for broadband coherent radiation generation*
- The technique was recently demonstrated in the optical domain**

- Study microbunching instabilities due to LSC in the chicane cascade
- Implement an efficient algorithm for 3D space charge force calculation
- Explore the possibility of the short wavelength radiation generation at FAST facility

*M. Dohlus, E. A. Schneidmiller, and M. V. Yurkov, *Phys. Rev. ST Accel. Beams*, **14**, *090702 (2011).*
A. Marinelli, et al., *Phys. Rev. Lett.*, **110, *264802 (2013).*

Space charge problem

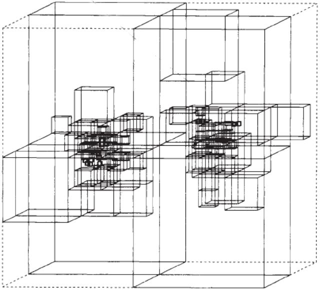
- Many numerical and analytical methods "reduce" the space charge problem's complexity which ultimately limits the maximum attainable spatial resolution
- Most of the LSC studies use a simple 1D model based on impedance approximation
- Space charge problem is very similar to the well-known *N*-body problem in celestial mechanics
- Very effective algorithm for the gravitational *N*-body problem, so called "tree" or Barnes-Hut (BH) algorithm can be used*

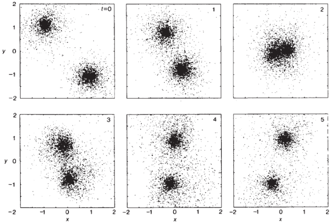
Some conventional codes: ASTRA, SYNERGIA, TSTEP

*J. Barnes and P. Hut, *Nature*, **324**, *446 (1986)*.

Tree algorithm for space charge force calculation

- Scales as $\mathcal{O}(N \log N)$, where N is the number of macroparticles used to represent the beam
- Precision parameter corresponds to the "depth" of the tree
- Can be applied to many-body systems

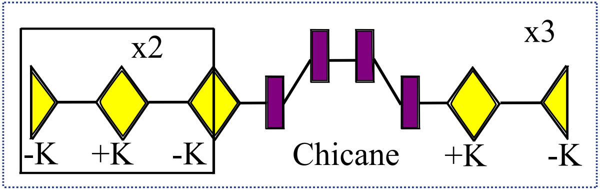




Images courtesy of J. Barnes

Longitudinal space charge amplifier (LSCA)

- Can serve as addition to an existing FELs and linacs (use existing beamlines to generate powerful radiation)
- Can be used as a source of radiation with a relatively large bandwidth
- Can produce very short radiation pulses



The yellow lozenges and purple rectangles respectively represent quadrupole and dipole magnets.

*M. Dohlus, E. A. Schneidmiller, and M. V. Yurkov, *Phys. Rev. ST Accel. Beams*, **14**, *090702 (2011).*

LSCA cont.

The estimated gain per one chicane in LSCA is proportional to space-charge impedance $Z(k, r)$:

$$\mathbf{G = Ck|R_{56}|\frac{I}{\gamma I_A}\frac{4\pi L_d|Z(k,r)|}{Z_0}\exp(-\frac{1}{2}C^2k^2R_{56}^2\sigma_\delta^2)}$$

The on-axis LSC impedance is given by:

$$\mathbf{Z(k) = -i\frac{Z_0}{\pi\gamma\sigma}\frac{\xi_\sigma}{4}e^{\xi_\sigma^2/2}\mathrm{Ei}(-\frac{\xi_\sigma^2}{2}), \quad \xi_\sigma = k\sigma/\gamma}$$

To characterize the current (density) modulation one can introduce the bunching factor

$$\mathbf{b(\omega) = \frac{1}{N}|\sum_n \exp(-i\omega t_n)|}$$

The broadband amplification process can be seen on the bunching factor curve as a broad peak.

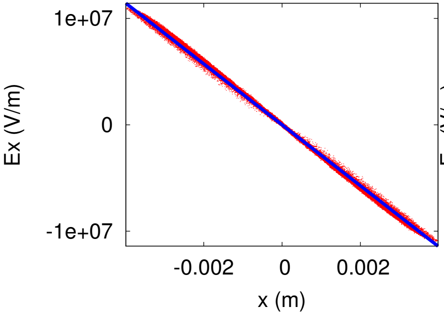
Procedure

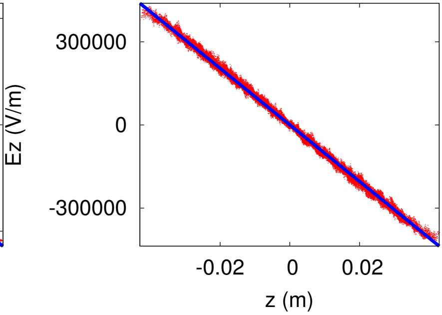
- BH algorithm is used as an external script within the ELEGANT simulations.
- The distribution at the specified location was saved and Lorentz transformation to the bunch rest frame was applied.
- The BH algorithm was used to obtain the 3D electrostatic field $\mathbf{E}'$. This field was then transformed in the laboratory frame and the obtained electromagnetic fields $(\mathbf{E}, \mathbf{B})$ were used to compute the Lorentz force on each of the macroparticles composing the beam.
- The distribution then was finally passed back to ELEGANT and tracked up to the next space-charge kick where the above process repeated.
- We assumed no transverse motion in the bunch rest frame.
- We made no assumptions on the distribution and/or bunch shape.
- The BH algorithm will be a part of ELEGANT when fully tested.

Validation

Compare computed fields (red dots) to Lapostolle analytical result (blue line) for the uniformly distributed ellipsoidal bunch ($u \in [x, y]$, $r_{x,y,z}$):

$$E_u(u) = \frac{C}{\gamma^2} \frac{(1-f)u}{r_u(r_x + r_y)r_z} \qquad E_z(z) = \frac{Cf}{r_x r_y r_z} z$$



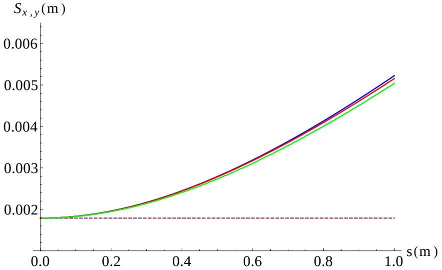


Validation cont.

To assess longer-term tracking, we compared the evolution of the beam envelope over a drift space. For a stationary uniform beam the transverse envelope evolution is governed by:

$$S''_{x,y} - \frac{\varepsilon^2_{rx,ry}}{S^3_{x,y}} - \frac{K}{2(S_{x,y} + S_{y,x})} = 0,$$

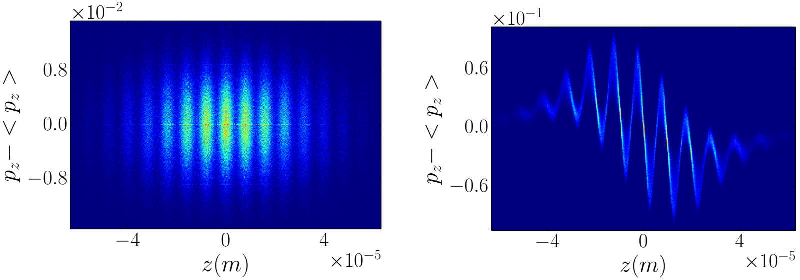
where $S_{x,y}$ is the rms beam size in x, y, $\varepsilon_{rx,ry}$ is the corresponding emittance and K is a 3D space charge parameter.



Envelope equation
ASTRA simulations
ELEGANT-BH simulations
No space charge case (low ε)

Phase space

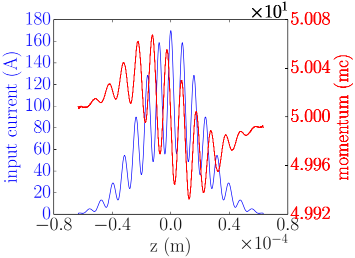
The longitudinal space charge impedance $Z(k)$ can be probed as a FFT image of the phase space

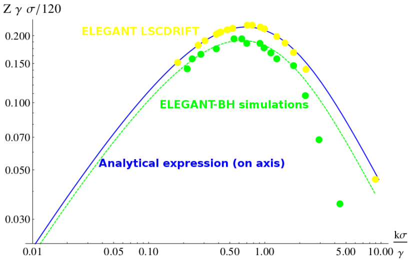


On the left: Initial modulation. *On the right:* Final modulation. This is repeated for every selected k to retrive $Z(k) \propto E(k)/I(k)$.

Validation cont.

Let's consider initial bunch distribution with pre-modulated current profiles of the form $\mathbf{f(r) = T(x,y)L_z(z)\,[1 + m\cos kz]}$

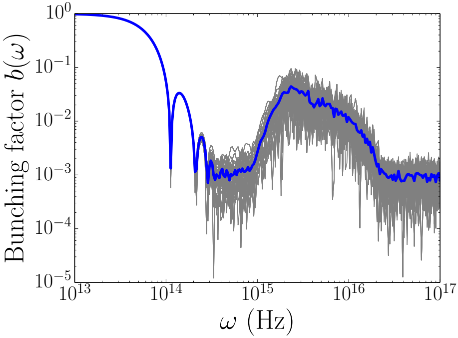




On the left: Initial density modulation resulted in energy modulation. *On the right:* The agreement between the BH algorithm and analytical impedance equation $\mathbf{Z(k) = -i\frac{Z_0}{\pi\gamma\sigma}\frac{\xi_\sigma}{4}e^{\xi_\sigma^2/2}Ei(-\frac{\xi_\sigma^2}{2})}$

Bunching factor (averaged)

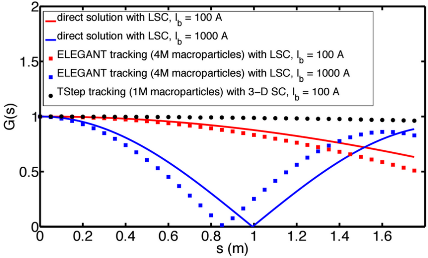
The LSC impedance results in selection of preferred frequency

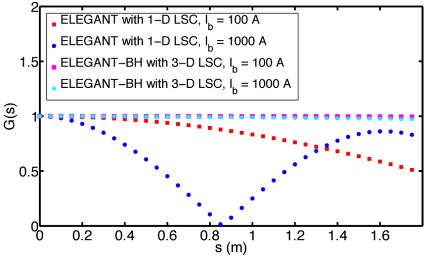


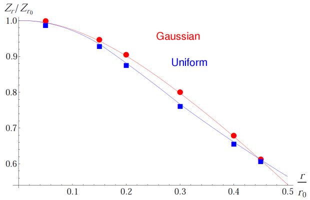
100 realizations with 1M particles (gray traces) and corresponding average (blue trace)

Three-dimensional effects

Microbunching gain along the drift





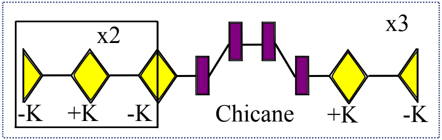


The results are consistent with TSTEP.

Three-dimensional effects are discussed in J. Wu, et al., *Phys. Rev. ST Accel. Beams*, **11**, *040701 (2008)*
Upper plots are courtesy of C.Y. Tsai (VA. Tech.)

Simulations

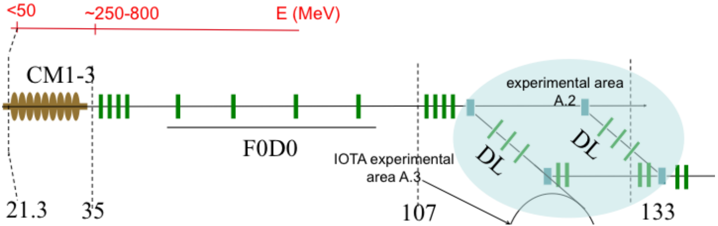
- The simulations consider the lattice diagrammed below consisting of three LSCA modules each composed of three FODO cells with a chicane integrated in the last FODO cell.
- The BH code performs full 3D space-charge calculation and therefore inherits both transverse and longitudinal effects.
- All simulations were done for ($N = [0.1..4] \times 10^6$) particles to ensure the convergence and satisfying the statistical limit.

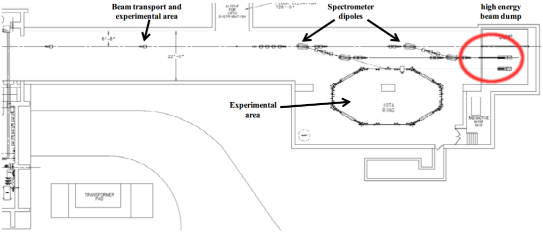


Fermilab Accelerator Science and Technology facility (FAST)

The FAST facility will soon comprise a 50-MeV injector followed by an accelerator cryomodule capable of booting the beam energy up to 300 MeV.

FAST cont.





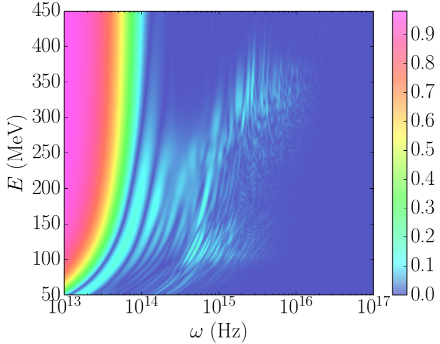
Possible use of the FAST beamline before the dump area

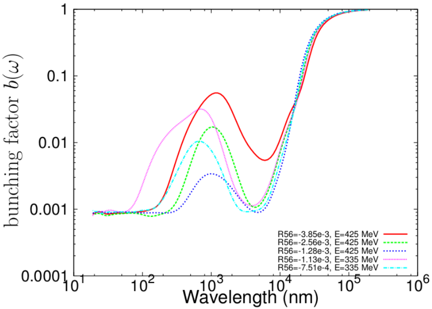
Bunch parameters

Parameter	Value	Units
Spotsize, σ	2.2 - 70.4	μm
Charge, Q	20.0	pC
Lorentz factor, γ	50 - 1000	–
Bunch duration, τ	120	fs
Norm. transv. emittance, $\varepsilon_{x,y}$	10^{-8}	m
Momentum spread, σ_δ	10^{-4}	–
Number of macroparticles, N	0.1 - 4	million
Total LSCA length, D	28.0	m

Energy scan

On the left: The change of the bunching factor vs energy of the bunch.

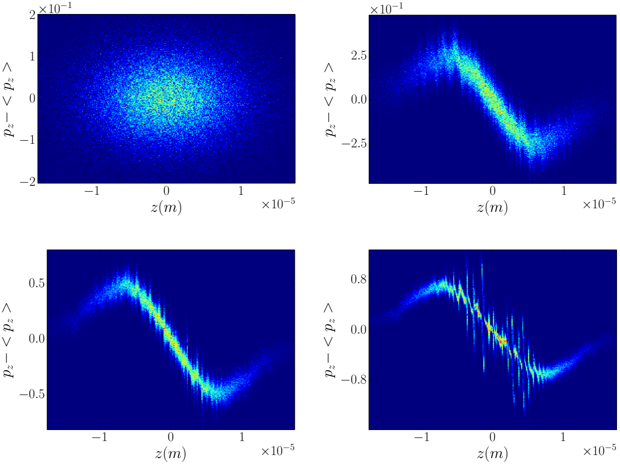




On the right: Spline-smoothed bunching factor for different values of the chicane longitudinal dispersion R_{56}.

Microbunching instabilities

Phase space of the Gaussian beam (left to right) before and after passing through one, two and three LSCA structures at $\gamma = 670$.



Possible LSCA at FAST

- Will not require much redesign of the lattice
- Can be compact (10-20 m)
- Can produce soft UV light. Still needs to be pushed for the VUV regime
- Local energy chirp can be made up-right to produce shorter pulses
- Some preliminary studies and discussion with collaborators at Jefferson Lab are on-going to check the possible use of IOTA to explore space charge microbunching instabilities relevant to electron-cooling ring for the electron-ion collider

Conclusions

- Using a gridless code adapted from Astrophysics we have investigated effects in the LSC impedance and found that the one-dimensional often used LSC impedance model is a good approximation.
- Nonetheless, our simulations consistently underestimate the analytical impedance over the range of k values explored. Such an effect was previously recognized and is attributed to the radial dependence of the LSC field conferring a similar dependence on the impedance.
- We demonstrated that LSCA can produce femtosecond pulses of light in optical regime.

Conclusions

- Adjusting the chicane parameter R_{56} can be a "single-knob" to generate light of a desired wavelength.
- The designed beamline at FAST facility allows proposed LSCA to be implemented and operate as a compact source of $100 - 1000$ nm light.
- It was shown that the LSCA can operate at various energies, what makes it possible to implement it at every FAST construction phase.

Credits

Acknowledgements:

- P. Piot (NIU, Fermilab) for supervising this research
- J. Barnes (U. Hawaii) for granting us use of his algorithm
- M. Borland (ANL) for his help and interest in including the algorithm into ELEGANT
- Rui Li (Jefferson Lab) and C.-Y. Tsai (Virginia Tech) for their interest and independent benchmarking of ELEGANT-BH

Thank you for your attention!